FOLLOW ON VALIDATION OF FORCE-LIMITED VIBRATION TESTING

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ABSTRACT

A second sounding rocket experiment was performed in the summer of 1998 in a continuing effort to validate the force limits techniques used in random vibration tests. The accuracy of the force limiting prediction techniques has not clearly been sufficiently confirmed with in-flight data as of this time. The flight was on board one of the Black-Brant series of sounding rockets. This vehicle is the one most commonly used for sub-orbital scientific payloads by NASA. An aluminum double deck structure simulating a dynamic source and load was flown. The hardware was instrumented with accelerometers and force sensors that measured input acceleration, forces and acceleration responses on the load. Force limiting analysis methods are compared with the flight measurements in order to evaluate analysis predictions methods and test procedures. This sounding rocket flight is the second in a series of flights that will be performed.

KEYWORDS

Vibration, Force Limiting, Sounding Rocket, Force Gages, Telemetry

INTRODUCTION

Typical shaker test specifications are generated based on a spectral envelope of maximum acceleration values measured throughout the flight. They conservatively represent the motion of the launch vehicle and payload system interface, although they are intended to be applied to the payload alone for mechanical test purposes. This is in essence overly conservative when the test article is excited by the automatic controlled motion of a relatively infinite impedance shaker.

Force limiting compensates for the launch vehicle characteristics missing during the shaker test. This paper follows on the findings encountered in a previous sounding rocket experiment performed back in 1997. [1]

OBJECTIVES OF EXPERIMENTS

The primary objective of the sounding rocket experiments is to continue the process of validating the force limited random vibration prediction methods and test procedures. This was accomplished in this flight by flying an improved experiment structure that could be easily and accurately modeled.

The secondary objective of the series of experiments is to obtain flight data that could be used to develop specifications for six degree of freedom vibration testing. This data was obtained from this flight but will not be discussed in this paper.

DESCRIPTION OF THE SECOND FLIGHT EXPERIMENT

BLACK BRANT SOUNDING ROCKET

The Black Brant series of sounding rockets are small multistage rockets that can send a payload on a sub-orbital flight with an apogee ranging from 400 to 1200 kilometers. Figure 1 is a sketch showing the Black Brant variant used in this flight. This version, which was used on the second flight, uses a Terrier booster and a Black Brant second stage.

The experiment package, which had a weight of 2 lb, was located in the adapter between the Antenna/Camera Section and the Recovery Section. The adapter is indicated with an arrow. The experiment in this second flight was recovered from the desert along with all sensors to be reused in the future as opposed to the first flight where the experiment was not recovered.
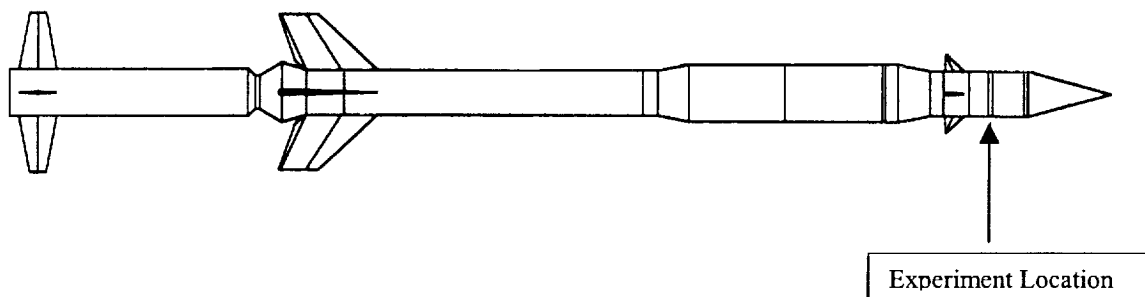

Experiment Location

Figure 1 – Black Brant Sounding Rocket

EXPERIMENT STRUCTURE

The experiment structure consists of a double deck aluminum plate which spanned the 15.08 inches of the sounding rocket section. A 1 lb mass or load portion was installed on

the 0.1 inch thick central plate. This plate was then mounted in each side to a 1 lb / 0.1 inch base aluminum plates or source. In between the source and load are located four force sensors. A photograph of the experiment structure already mounted in the rocket section is shown in figure 2. The flight qualification of the experimental deck is not the focus of this paper. The structure was designed and qualified to higher levels than expected. Ground hammer and shaker testing are used to improve the experiment models, recreate a hypothetical qualification test and assess the merits of several force limiting methods and test procedures.
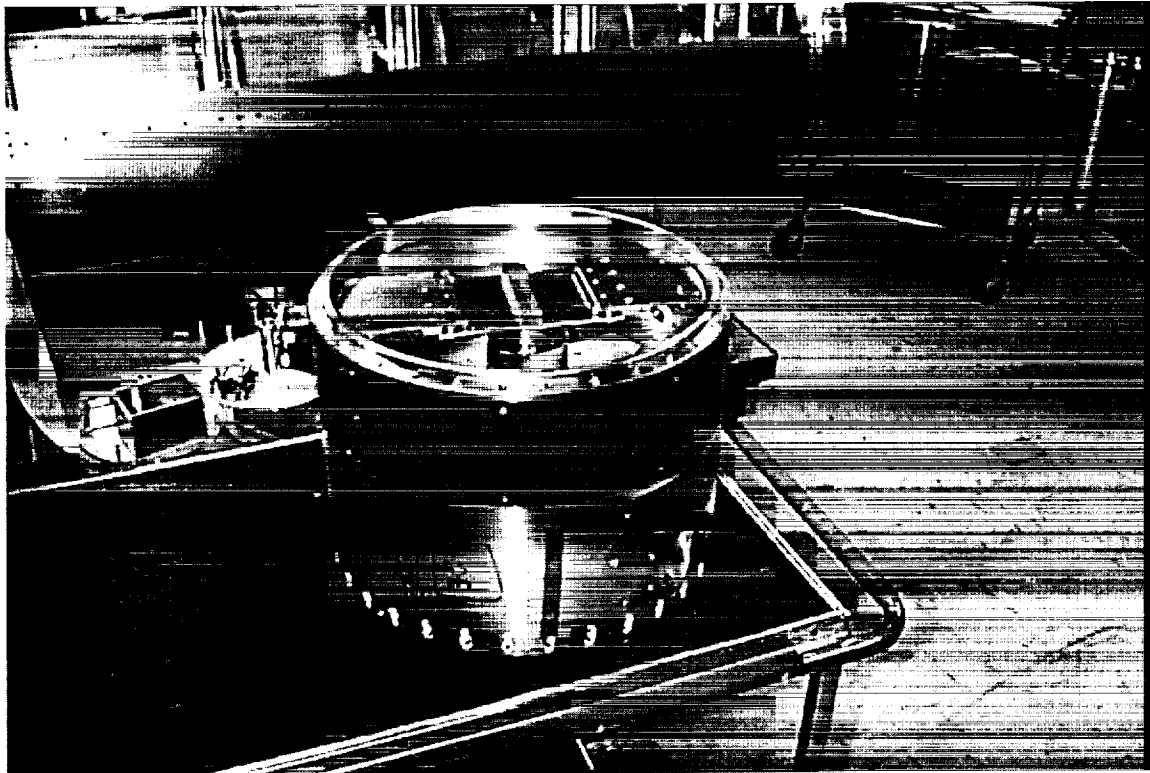

Figure 2. Photograph of the Experiment Structure

TRANSDUCERS

The experiment structure was instrumented with Nine Endevco 7257AT-100-501 accelerometers and four PCB 9101A force transducers. Two accelerometers measured the input to the central plate and one accelerometer measured the response. Six accelerometers measured the source input along the three degrees of freedom. The four force transducers measured the forces at the source to load interface. Figure 3 shows the location of the transducers on the test structure. Charge amplifiers and 500 Hz filters were internal to the accelerometers. A sample rate of 2500 samples/seconds was used. All the analysis was performed in the 20-500 Hz range.
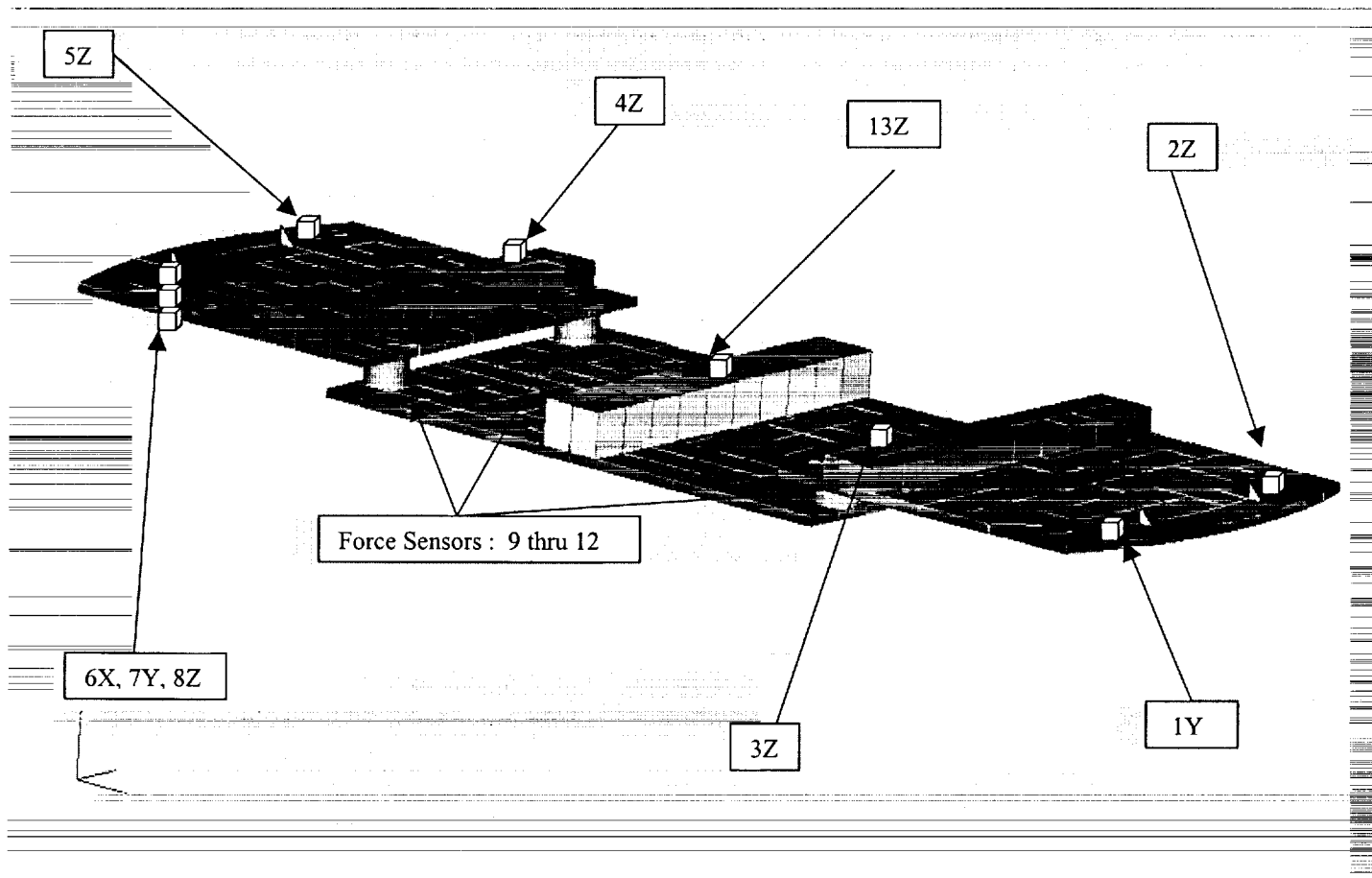
Figure 3. Experiment Instrumentation

TELEMETRY

The telemetry system, designed and constructed by the Wallops Flight Facility (WFF), consisted of a single down link S-Band system. It used Pulse Code Modulation (PCM) to transmit the accelerometer and force transducer data. An Aydin Vector MMP-900 series PCM encoder was used which operated at 800 Kilobits/second with Biϕ - L code, 10 bit word length, and sixteen words by one frame in size. The PCM output modulated a two-watt S-Band transmitter, with a carrier frequency of 2241.5 MHz, through two blade antennas.

PREFLIGHT TESTS

The experimental deck was qualified for flight using the sounding rocket "Vibration Test Levels for New Payloads" at "Vehicle Level Two" [2] in the thrust axis only. A force limited test was not conducted before flight since, as previously stated, the experimental deck acted as a test bed for later testing using the actual flight input acceleration. Pre-flight hammer test were performed on the source, and shaker test were performed on the load in order to assess the expected dynamic characteristics of the experimental deck. A summary of these tests is presented in the following sections.

SOURCE IMPEDANCE

Before the payload was flown, source impedance measurements were made using a modal hammer and an HP 3565 signal analyzer. When the rocket is put together, there is no room to tap on the experiment source. The source was therefore tapped in two configurations. The first one when mounted to the cone or front section of the rocket, the second one when mounted to the payload or rear section.

Analytical source impedance was also derived and compared with the collected data. In the analytical case only a cantilevered source plate was represented since the rocket model was unavailable. These results are shown in figure 4.

The front and rear impedances look similar, this means that the experimental source was designed correctly and its dynamics dominate over the remaining rocket structure in the frequency range under consideration. This assumption is further confirmed by the analytically derived impedance which also exhibits similarity with both. The experimental data was used in the force limit calculations.
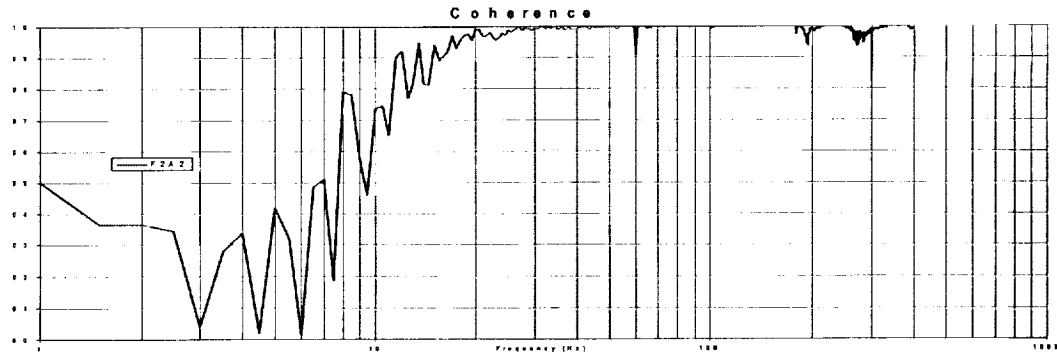
Hammer Test vs FEM
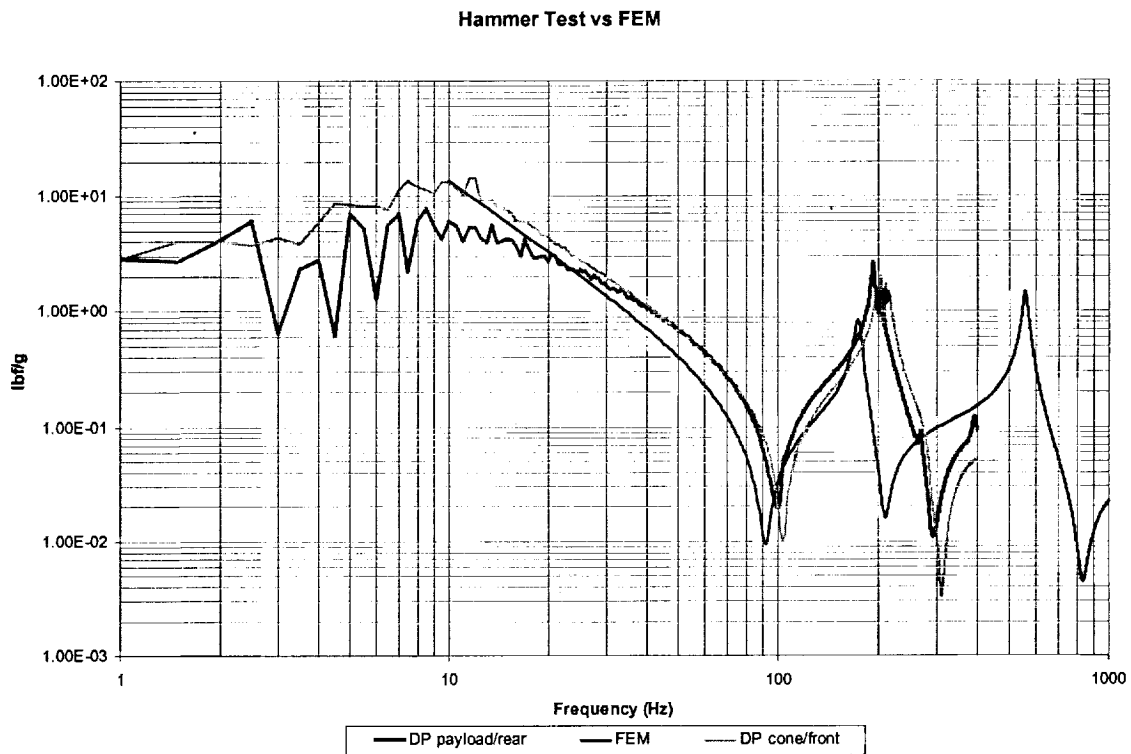
Figure 4. Source Impedance

LOAD IMPEDANCE

Shaker test load impedance was measured for a 1/4-g sine sweep test and also recovered from the full level random. These measurements were obtained by summing the force transducer responses electronically and computing a Frequency Response Function (FRF) using one of the input accelerometers as a reference. The results are shown in figure 5.
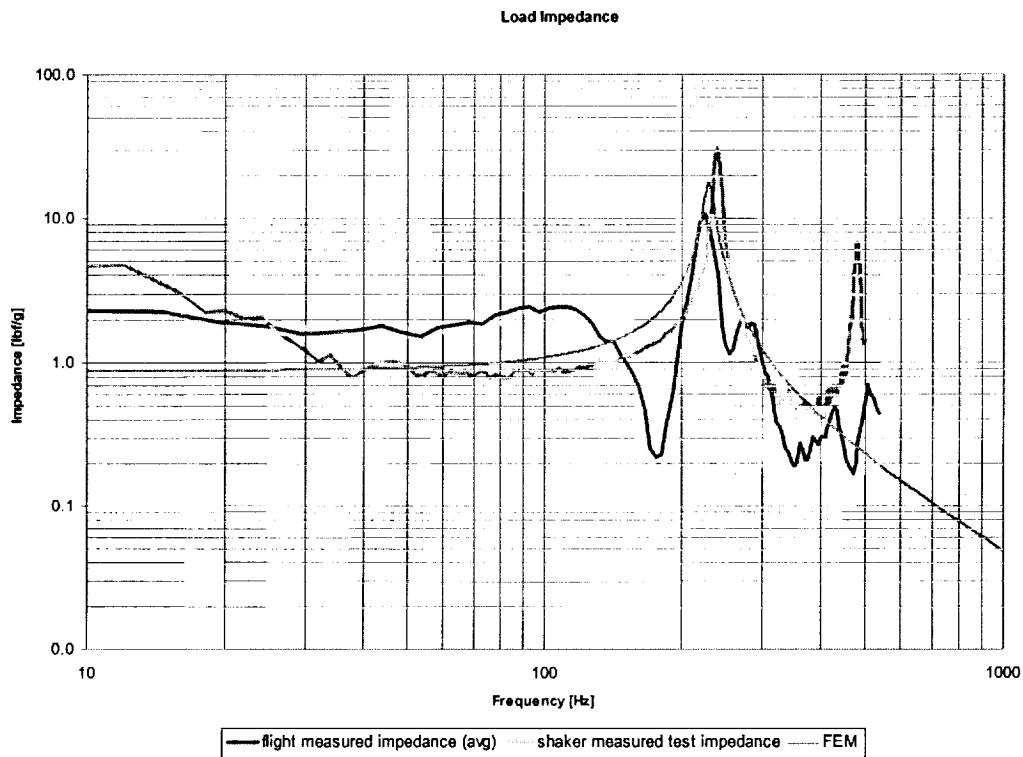
Load Impedance

Figure 5 – Load Impedance (flight, shaker & FEM)

FLIGHT RESULTS

The experiment was flown in the summer of 1998. Data from all telemetry channels was successfully collected for the entire flight — from launch to parachute recovery.
The telemetry data was transferred to CD-ROM and processed using a combination of MATLAB, SDRC/IDEAS, Microsoft EXCEL, and WinDAP, a windows-based data processing package developed by the co-author. These results are discussed in the following sections.

ACCELERATION-TIME HISTORIES

Figure 6 shows the accelerometer time-histories obtained during the boost phase of the flight. All of the records show the same sequence of events: launch (~1 second); Terrier separation and ignition of Black Brant (~12 seconds); end of the Black Brant burn (~42 seconds). The other few spikes present in the records are dropouts in the telemetry system downlink.

The three Z-axis shell accelerometers (Channels 2, 5, and 8) all show similar characteristics indicating that the data was valid. The two Z-axis plate accelerometers (Channels 3 and 4) agree which each other as well. There appears to be some amplification of the shell signal due to plate system resonance at the end of the Black Brant burn. The single Z-axis response accelerometer (Channel 13) also shows a slight increase due to this resonance.

The three lateral accelerometer signals (Channels 1, 6, and 7), used for six degree of freedom measurements, also appear to agree with one another.
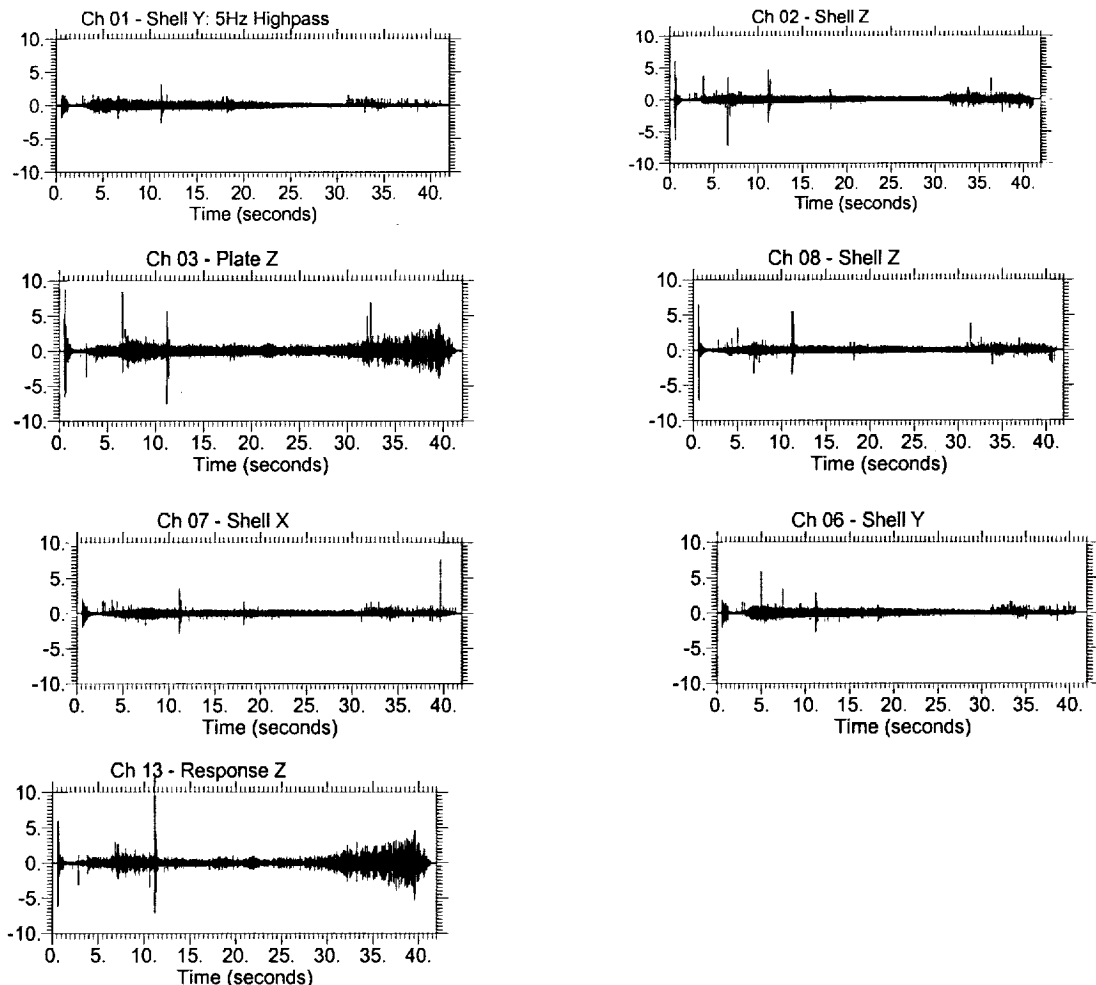
Figure 6 – Accelerometer Time Histories

FORCE-TIME HISTORIES

The force transducer responses, shown in figure 7, also indicate good results. They show the same sequence of flight events as the accelerometers. The force transducers indicate a buildup in interface forces towards the end of the Blank Brant burn.
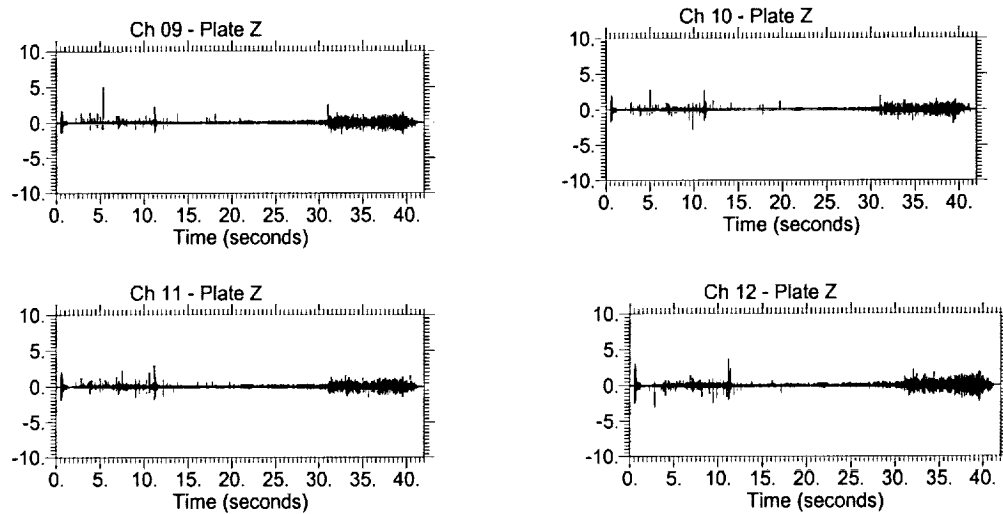

Figure 7 – Force Time Histories

INPUT PSD

Due to the non-stationary nature of the data, the input acceleration was processed into PSDs at two-second intervals with the transient events not processed. The resulting group of PSDs is displayed for several flight time periods in plot in figure 8. The plot shows a fairly flat spectrum during the Terrier burn and in the early part of the Black Brant burn. Later in the Black Brant burn, resonances appear at 120 Hz, 170 Hz and 320 Hz. The 220 Hz load range does not show resonance in the flight (coupled system).
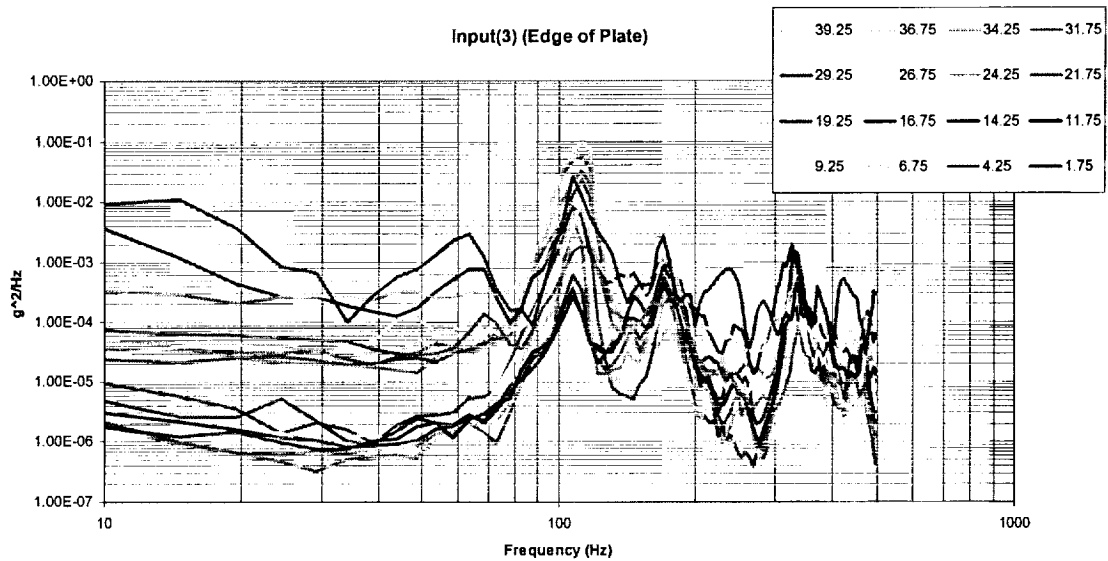
Figure 8 – Input PSD's

RESPONSE PSD

The response accelerometer PSD for several flight time periods, plotted in figure 9, shows predominant resonances at 120 Hz, 220 Hz and 320 Hz throughout the flight. There is also a resonance at 60 Hz during the Terrier portion of flight. Except at these three resonances, the levels were lower than the input acceleration.
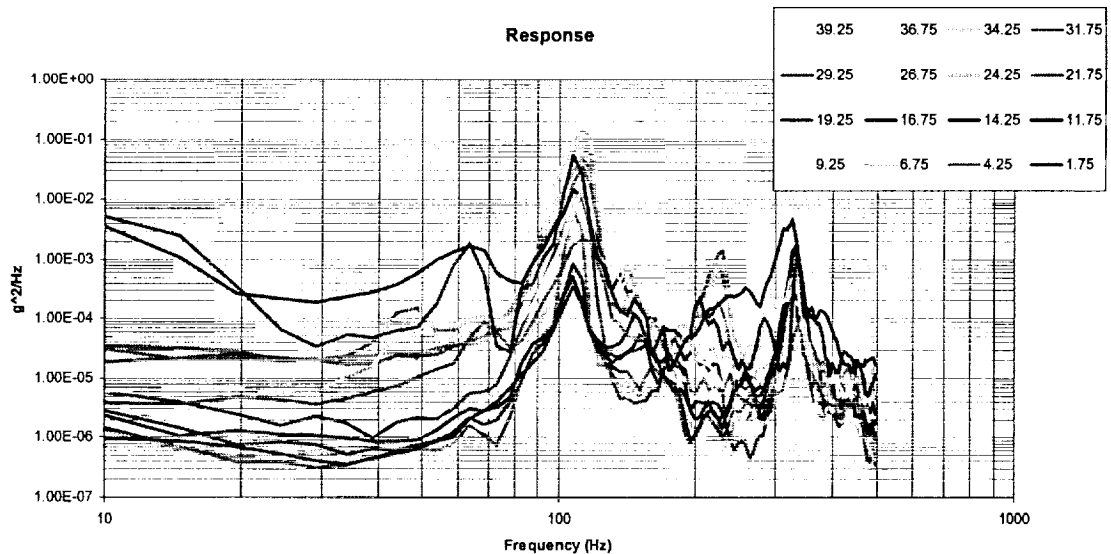

Figure 9 – Response PSD's

INTERFACE FORCE SUM PSD

The force gages where summed in the time domain and then a PSD was performed on them. The interface force sum PSD for several flight time periods, plotted in figure 10, shows only the predominant resonances at 120 Hz throughout the flight.
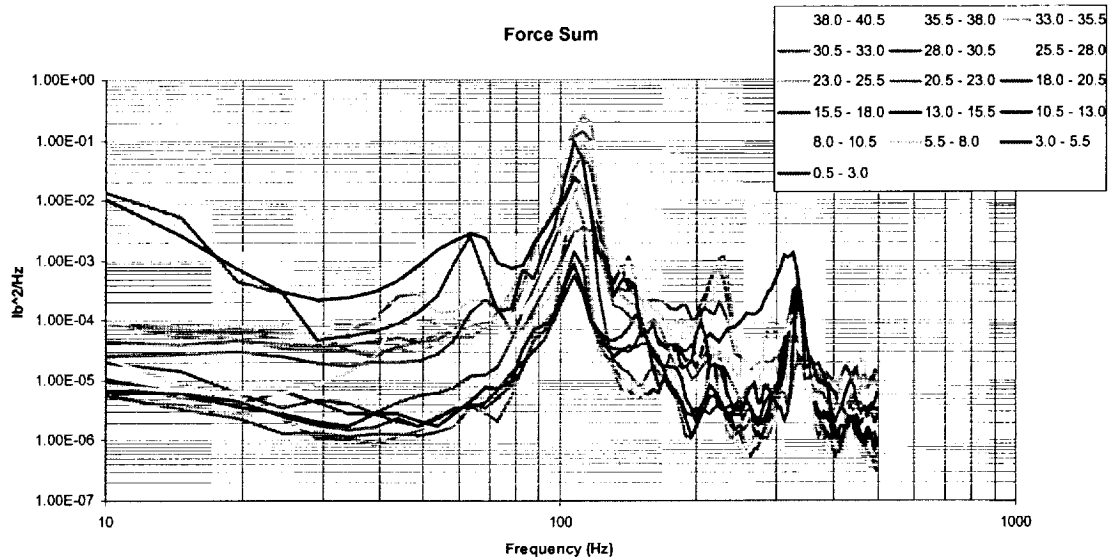

Figure 10 – Force PSD's

POSTFLIGHT EVALUATION AND VIBRATION TESTS

A duplicate test structure was fabricated and instrumented at the identical locations that were used in flight. Source, load and input data were used to evaluate force-limiting methods and proceed to force limited and nonlimited random vibration tests of the load. The methods, evaluation, and test results are described in the following sections.

FORCE-LIMITED VIBRATION METHODS

The blocked force (source impedance method), force acceleration (FA) and modified Murfin (MM) (load impedance methods), simple and complex two degree of freedom (STDF, CTDF, combined methods) and semi-empirical method (SE) were evaluated [3]. In addition a maximax force and its peak envelope (typical test specification) were used.

Figure 11 presents a comparison of each method with respect to the maximax flight interface force measured (maximum value in each one-third octave band). Table 1 presents the same information in a different format and includes a comparison of force root mean square (rms) values. All the data was evaluated in one-third octave frequency bands for this comparison.

In order to evaluate the results, the author would like to focus the attention to the following regions: (1) low frequency non resonant (in this case up to the 80 Hz octave), (2) the coupled system resonant region (first resonance located at the 125 Hz octave), (3) the first load resonant frequency (250 Hz octave) and (4) the high frequency portion, say above and including the 300 Hz octave. It is also helpful at this time to remember that the load resonant region would be of particular interest because the random vibration test is acceleration controlled but force limited only. Hence we are expecting the force limit to kick in only in that region of the load. Overall force rms predictions are also useful, although not very practical when the acceleration specification is an envelope because the resulting force rms will be a large value.

It can be observed that the blocked force method is the most conservative in region (1), but not necessarily so in regions 2) and (3). The STDF is conservative also in regions (1) and (2) but marginal in region (3). The CTDF is conservative in most of regions (1) and (2) as well as in region (3). This shows that CTDF is a good predictor for the load resonant frequencies. FA and MM are similar to the CTDF and complement very well with it. Finally the SE computed here was defined for a scale factor of 1 (lower force limit bound for the author), cut off frequency in the 250 Hz octave and roll of factor of 2. The SE proved non-conservative in (3). Most methods are conservative in region (4), except for the 315 Hz octave. The most conservative results are found when a maximax is applied or even more when a peak envelope is used. In that case, all the predictions are above the flight measurements. Table 1 also presents the maximum and minimum difference between the method and the flight measurements for a particular octave, as well as the average throughout the overall frequency range.
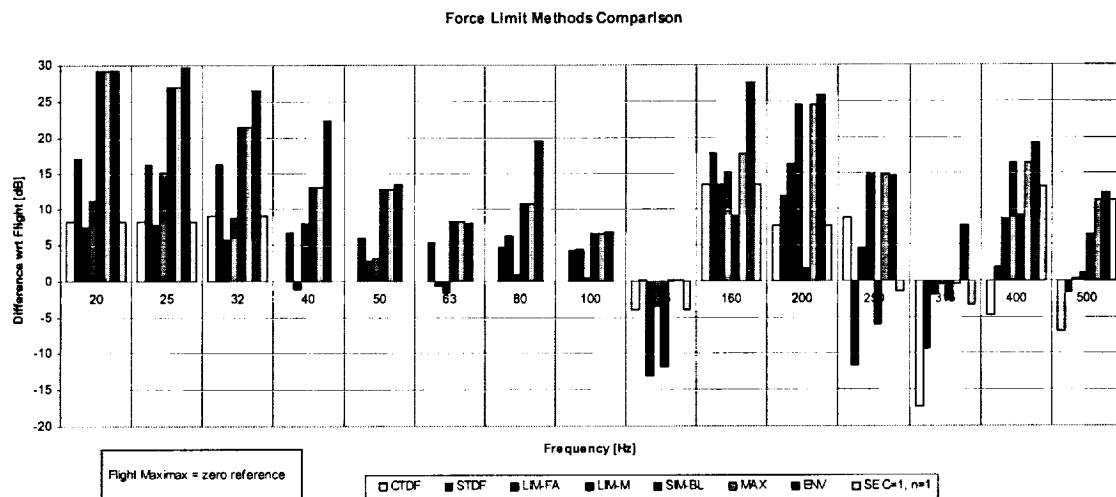

Figure 11 – Force Limit Methods Comparison

Freq.[Hz]	STDF[dB]	CTDF[dB]	LIM-FA[dB]	LIM-MF[dB]	SIM-BF[dB]	SEc=1,n=2[dB]	MAX[dB]	ENV[dB]
20	17.2	8.3	7.5	11.2	29.2	8.3	29.2	29.2
25	16.4	8.2	7.9	15.1	27.1	8.2	27.1	29.6
32	16.4	9.0	5.8	8.7	21.6	9.0	21.6	26.5
40	6.7	0.0	-1.1	7.9	13.2	0.0	13.2	22.3
50	6.0	0.0	2.9	3.2	12.8	0.0	12.8	13.5
63	5.4	0.0	-0.7	-1.6	8.3	0.0	8.3	8.0
80	4.7	0.0	6.2	0.8	10.9	0.0	10.9	19.5
100	4.2	0.0	4.4	0.5	6.6	0.0	6.6	6.8
125	0.2	-4.0	-13.0	-3.5	-11.9	-4.0	0.2	0.2
160	17.7	13.6	13.4	15.2	9.2	13.6	17.7	27.5
200	11.9	7.7	16.3	24.5	1.7	7.7	24.5	25.7
250	-11.7	8.7	4.6	15.0	-6.0	-1.4	15.0	14.7
315	-9.2	-17.4	-1.9	-0.6	-2.7	-3.4	-0.6	6.7
400	1.9	-4.8	8.6	16.4	9.1	13.2	16.4	17.1
500	-1.6	-7.0	0.3	1.1	6.4	11.2	6.4	9.3
max	17.7	13.6	16.3	24.5	29.2	13.6	29.2	29.6
avg	5.7	1.5	4.1	7.6	9.0	4.2	14.0	17.1
min	-11.7	-17.4	-13.0	-3.5	-11.9	-4.0	-0.6	0.2
overall rms[%]	52%	-3%	-25%	4%	360%	-6%		

Table 1 – Force Limit Methods Comparison

INPUT TEST ACCELERATION

Figure 12 presents input acceleration plots. One is the flight maximax of input locations 3Z and 4Z, the other two are the ones implemented in the shaker tests with and without force limits. Also shown in the figure are the 10 dB notches at 265 Hz and 330 Hz, along with additional reductions at 370 Hz and 420 Hz that are generated during the force limited vibration test. Flight and no limiting plots coalesce in the analysis range, having both measure 1.28 Grms. When force-limiting is applied, the input is reduced to 1.19 Grms.
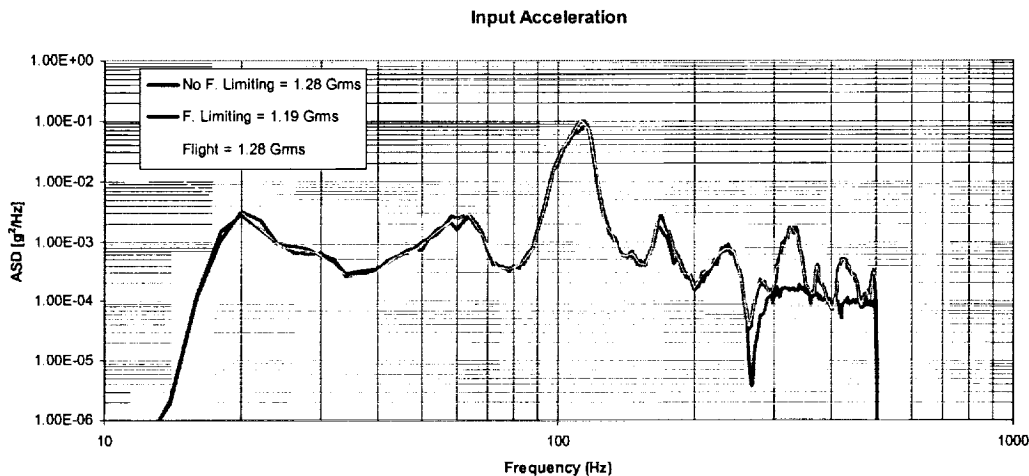

Input Acceleration

Legend:
- No F. Limiting = 1.28 Grms
- F. Limiting = 1.19 Grms
- Flight = 1.28 Grms

Y-axis: ASD [g²/Hz]
X-axis: Frequency (Hz)

Figure 12 – Input Acceleration

RESPONSE TEST ACCELERATION

Figure 13 presents response acceleration plots. One is the flight maximax of response location 13Z, the other two are the ones obtained in the shaker tests with and without force limits. It shows that the 120 Hz portion is non resonant for the load, hence flight and test are responding accordingly. The load resonance at 265 Hz is notched as well as the 330 Hz, 370 Hz, and 420 Hz. Flight and no limiting plots do not coalesce this time, as expected, due to differences in the dynamics of the systems involved. One of them is the coupled system (flight) and the other the load alone. The force-limited response has a Grms value in between flight and no limiting as expected. The difference of 25 % between limited and non-limited represents the amount of over-test that would have been present in the classical acceleration controlled test. The difference of 23 % between limited and flight represents the amount of conservatism in the force limits proposed.
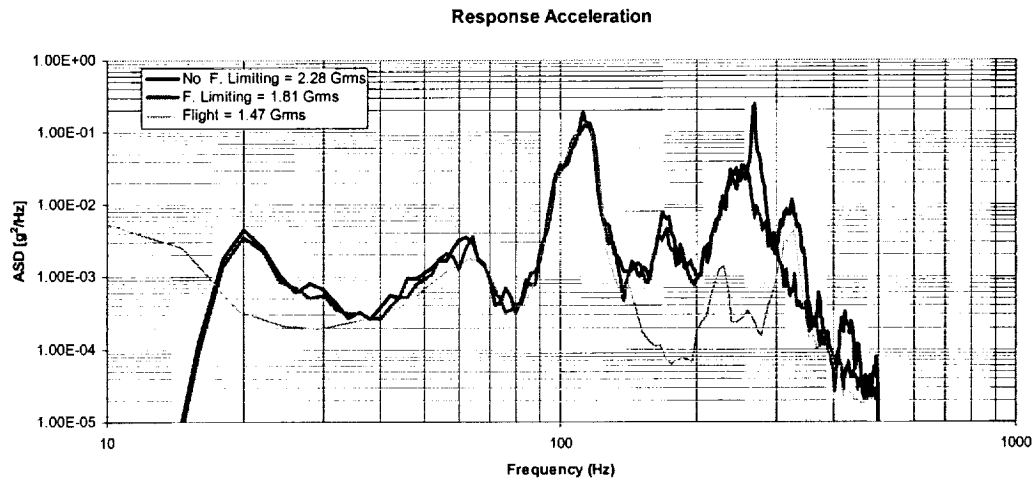

Response Acceleration

Figure 13 – Response Acceleration

FORCE SUM

Figure 14 presents the force plots. One is the flight maximax, the other two were obtained in the shaker tests with and without force limits. Again the force limited response has a Grms value in between flight and no limiting, as expected. The force limits used for the shaker tests were a combination of the above-explained methods chosen by the authors.
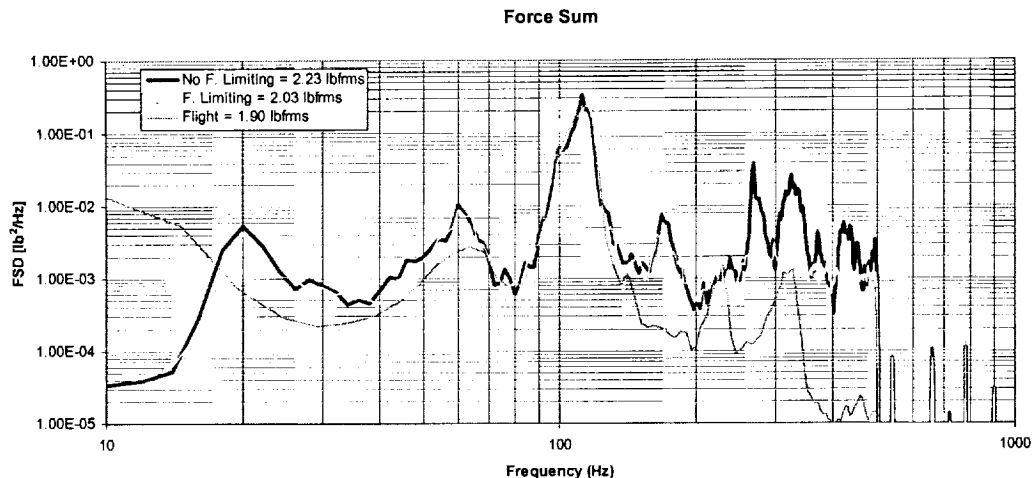
Force Sum

Figure 14 – Force Sum

CONCLUSIONS

In this paper study case, the acceleration specification was just the maximax bare bones (envelopes were not used) in order to better focus on the analytical methods.

The best methods have been found to be the CTDF, FA and MM in terms of getting closer to the flight predictions in a one-third octave band basis and overall force rms. The later is proportional to the overall response acceleration of the load during the flight or test. Close attention should be paid to the overall predicted force rms (before enveloping) as complementary criteria for adjusting the force spectral density limits at the load resonant frequencies.

The evaluation also shows the conservatism involved in enveloping a combination of methods. This is usually the case for a practical test implementation.

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BIOGRAPHIES

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Daniel Kaufman is the Manager of Mechanical Environments and Tests for the Space Systems Group, Orbital Sciences Corporation, where he is currently responsible for coordinating operations between the Mechanical Engineering Directorate and Environmental Test Groups. He has worked in the aerospace field for 15 years. He has a degree in Aeronautical Engineering and a Post-Graduate degree in Aerospace Technology from the National Technological University in Buenos Aires, Argentina. He is also an Advisor of the Aerospace Testing Seminar Board.

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Dan has been a test engineer in the Structural Dynamics Test Engineering Section at NASA/Goddard Space Flight Center since 1995 where he is involved in all aspects of vibration, acoustic, and modal testing of spacecraft and spacecraft components. Dan is a Technical Editor of the Journal of the IEST, a member of the SAVIAC Technical Advisory Group and serves on the AIAA Structures Technical Committee and the AIAA Dynamic Space Simulation Working Group. He is a recipient of a NASA Medal for Exceptional Achievement. Previously, Dan worked at the Naval Surface Warfare Center for fifteen years in the area of shipboard and pyrotechnic shock testing. He received a BSEE from Drexel University in 1980.